Eddy Resolving Global Ocean Prediction including Tides

Alan J. Wallcraft
NRL Code 7323
Stennis Space Center, MS 39529-5004
phone: (228) 688-4813 fax: (228) 688-4759 email: Alan.Wallcraft@nrlssc.navy.mil

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LONG-TERM GOALS

Use the HYbrid Coordinate Ocean Model (HYCOM) with tides, dynamic sea ice, and data assimilation in an eddy-resolving, fully global ocean prediction system with 1/25° horizontal resolution that will run in real time at the Naval Oceanographic Office (NAVOCEANO) starting in FY14. The model will include shallow water and provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model.

OBJECTIVES

To develop, evaluate, and investigate the dynamics of 1/25° global HYCOM (HYbrid Coordinate Ocean Model) with tides coupled to CICE (Los Alamos Community Ice CodE) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Also to incorporate advances in dynamics and physics from the science community into the HYCOM established and maintained within the Navy.

APPROACH

Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, pressure levels (nearly fixed depths) provide high vertical resolution in the mixed layer, and σ-levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation. HYCOM use a C-grid, has scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and has a data assimilation capability.

Global HYCOM with 1/12° horizontal resolution at the equator (~7 km at mid-latitudes) is the ocean model component of the Global Ocean Forecast System (GOFS) 3.02 which is currently running in real time on an IBM iDataPlex at the Naval Oceanographic Office (NAVOCEANO) and which was declared operational on 20 March 2013. It provides nowcasts and forecasts of the three dimensional global ocean environment. See http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html for movies, snapshots and comparisons to observations and http://www.hycom.org for model fields. The other major component of GOFS 3.02 is the NRL Coupled Ocean Data Assimilation (NCODA) which

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is a 3DVAR scheme that assimilates surface observations from satellites, including altimeter and Multi-Channel Sea Surface Temperature (MCSST) data, sea ice concentration and also profile data such as XBTs (expendable bathythermographs), CTDs (conductivity temperature depth) and ARGO floats (Cummings, 2005). By combining these observations via data assimilation and using the dynamical interpolation skill of the model, the three dimensional ocean state can be accurately nowcast and forecast.

HYCOM has been coupled to the Los Alamos Community Ice CodE (CICE) (Hunke and Lipscomb, 2004) via the Earth System Modeling Framework (ESMF) (Hill et al., 2004). Coupling between the ocean and sea ice models more properly accounts for the momentum, heat and salt fluxes at the ocean/ice interface. GOFS 3.1, developed under this project, will include HYCOM coupled to CICE at 1/12° horizontal resolution.

The principal goal of this project is to perform the necessary R&D to prepare to provide a next-generation ocean nowcast/forecast system with real time depiction of the three-dimensional global ocean state at fine resolution (1/25° on the equator, 3.5 km at mid-latitudes, and 2 km in the Arctic). A major sub-goal of this effort is to test new capabilities in the existing 1/12° global HYCOM nowcast/forecast system and to transition some of these capabilities to NAVOCEANO in the 1/12° system, and others in the 1/25° global system. The new capabilities support (1) increased nowcast and forecast skill, the latter out to 30 days in many deep water regions, including regions of high Navy interest such as the Western Pacific and the Arabian Sea/Gulf of Oman, (2) boundary conditions for coastal models in very shallow, and (3) external and internal tides, the latter will initially be tested at 1/12°, to minimize computational cost, but will transition to NAVOCEANO only in the 1/25° system because at this resolution it will replace regional models with tides (all these will greatly benefit from the increase to 1/25° resolution). In addition to the NRL core tasking covered here, this effort will collaborate with a core team of similar size at FSU COAPS, with other parties interested in HYCOM development, and ONR field programs to test and validate the model in different regions and different regimes. Demonstrated advancements in HYCOM numerics and physics from all sources will be incorporated through this project.

WORK COMPLETED

The first 1/25º global HYCOM simulations (3.5 km resolution at mid-latitudes) were run four years ago with climatological 6-hourly atmospheric forcing. Three years ago we extended the simulation for 2003-2010 with 3-hourly NOGAPS atmospheric forcing, but still without data assimilation. Last year we repeated this process with 41 layers (up from 32 layers) and coupled to CICE.

We ran the very first eddy resolving (1/12°) 3-D global ocean simulation with standard atmospheric forcing and tides in FY08 (Arbic et. al., 2010). Three years ago we performed a second multi-year simulation with an improved bottom tidal drag field, which was an exact twin of the 2003-2010 NOGAPS forced case mentioned above. Since then, the results of these new simulations were extensively analyzed and were the subject of multiple papers.

Two years ago we made several improvements to how we handle tides: (a) a new bottom drag field based on bottom roughness from the 30" GEBCO_08 bathymetry, (b) a 48-hour filter on near-bottom currents, for tidal bottom drag, that stops all semi-diurnal tides but passes 70% of diurnal tides, and (c) a spatially varying “scalar” approximation to self-attraction and loading. In addition new 1/12° and 1/25° bathymetries were produced, also based on 30" GEBCO_08. With these improvements in hand,

we started our 3rd global 1/12° simulation with NOGAPS and tides and the very first such global simulation at 1/25°. These were completed last year. In addition we have run a global 1/12° simulation with HYCOM coupled to the Los Alamos Community Ice CodE (CICE) via the Earth System Modeling Framework (ESMF) with NOGAPS and tides.

The Arctic Cap Nowcast/Forecast System (ACNFS) consists of the subset of our tri-pole 1/12° global HYCOM domain that is north of 40°N (3.5 km resolution near the North Pole, 6.5 km at 40°N) coupled to CICE via tESMF with NCODA 3DVAR data assimilation of ocean state and sea ice concentration. It has run in hindcast mode from July 2007 and in real time since June 2010. It has passed its OPTEST and now runs on an IBM iDataPlex at NAVOCEANO. For movies, snapshots and comparisons to the NIC frontal analysis, see http://www7320.nrlssc.navy.mil/hycomARC.

RESULTS

The FY13 ONR report by our collaborator Brain Arbic includes results from this past year obtained by Shriver and Richman at NRL under this project. These results will not be repeated here. However, one additional aspect of Jay Shriver's work on internal gravity wave stationarity is discussed below.

The stationarity of the internal tides generated in a high resolution global ocean circulation model was examined using results from years 2005-2009 of a seven and a half year 1/12.5° global simulation that resolves internal tides, along with barotropic tides and the eddying general circulation. We examined tidal amplitudes computed using 18 183-day windows that span the period 2005-2009. The 183-day window size is the minimum necessary to properly resolve the eight tidal constituents in HYCOM. The main metric used to evaluate stationarity is normalized RMS amplitude variations (amplitude standard deviation across the windows normalized by the mean amplitude), where large (small) fractional changes in relation to internal tide amplitude suggest non-stationarity (stationarity). Figure 1 shows the normalized RMS variability for the 4 semidiurnal (a-d) and 4 diurnal (e-h) internal tidal constituents in global HYCOM with regions where tidal amplitudes are less than 0.5 mm excluded. The diurnal and semidiurnal hot spot regions from Shriver et al. [2012] are denoted by black boxes, and in these boxes the internal tides are relatively stationary (even though the size of the non-stationary signal may be large on an absolute scale) for the 5 largest tidal constituents. For the 3 smallest amplitude constituents, K_2, P_1 and Q_1, a different picture emerges with much larger normalized RMS variability suggesting non-stationary internal tides. However, the probability distribution for these constituents resembles a Cauchy distribution expected for the ratio of two random numbers. The amplitudes of these weak constituents thus can’t be reliably estimated.

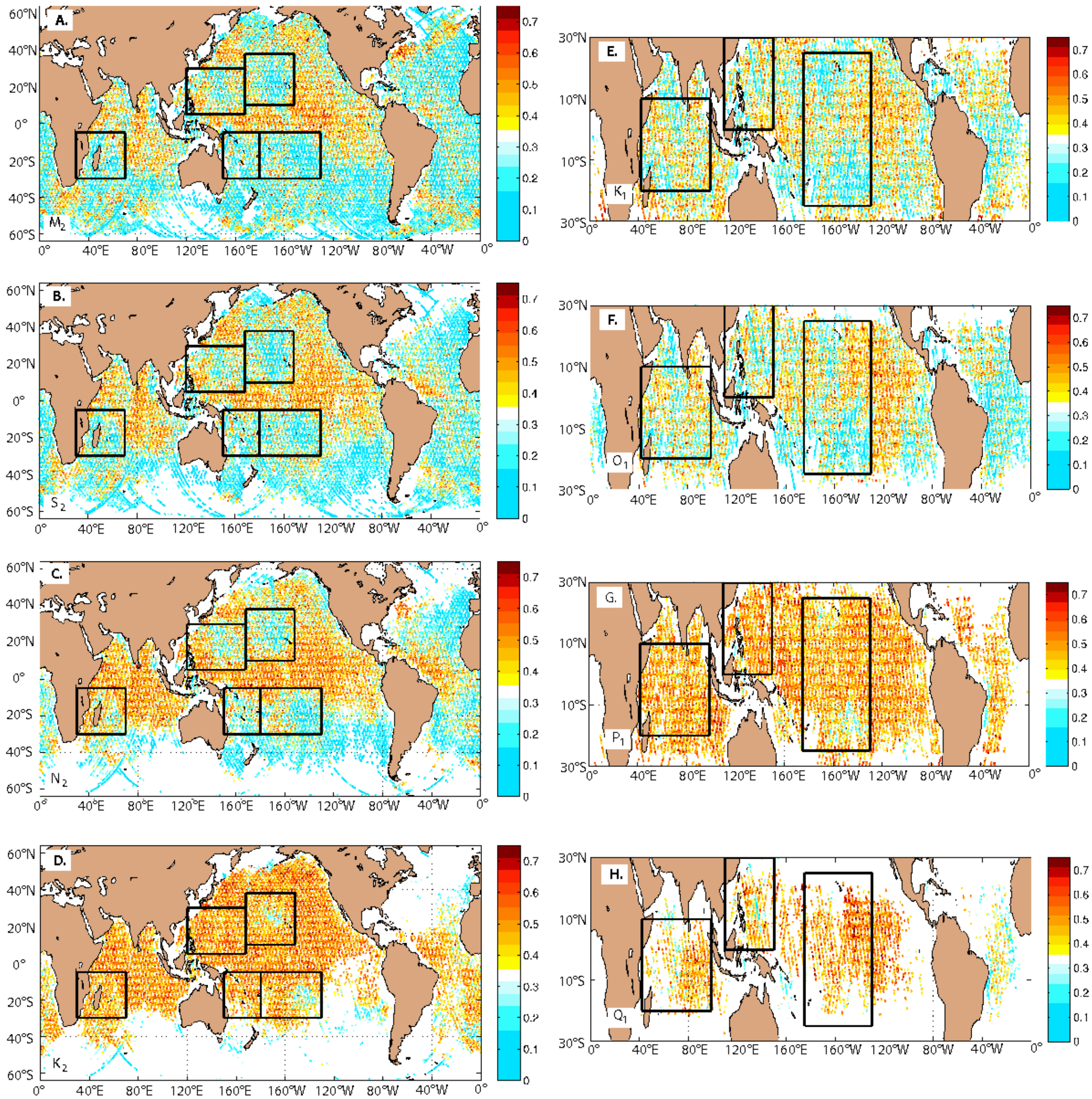

Figure 1. Normalized RMS variability for the 4 semidiurnal (a-d) and 4 diurnal (e-h) internal tidal constituents in global HYCOM with regions where tidal amplitudes are less than 0.5 mm excluded. Statistics were computed over eighteen 183-day data windows. The diurnal and semidiurnal hot spot regions from Shriver et al. [2012] are denoted by black boxes. In (e-h) the latitude range is restricted to the theoretical range where diurnal internal tides exist.

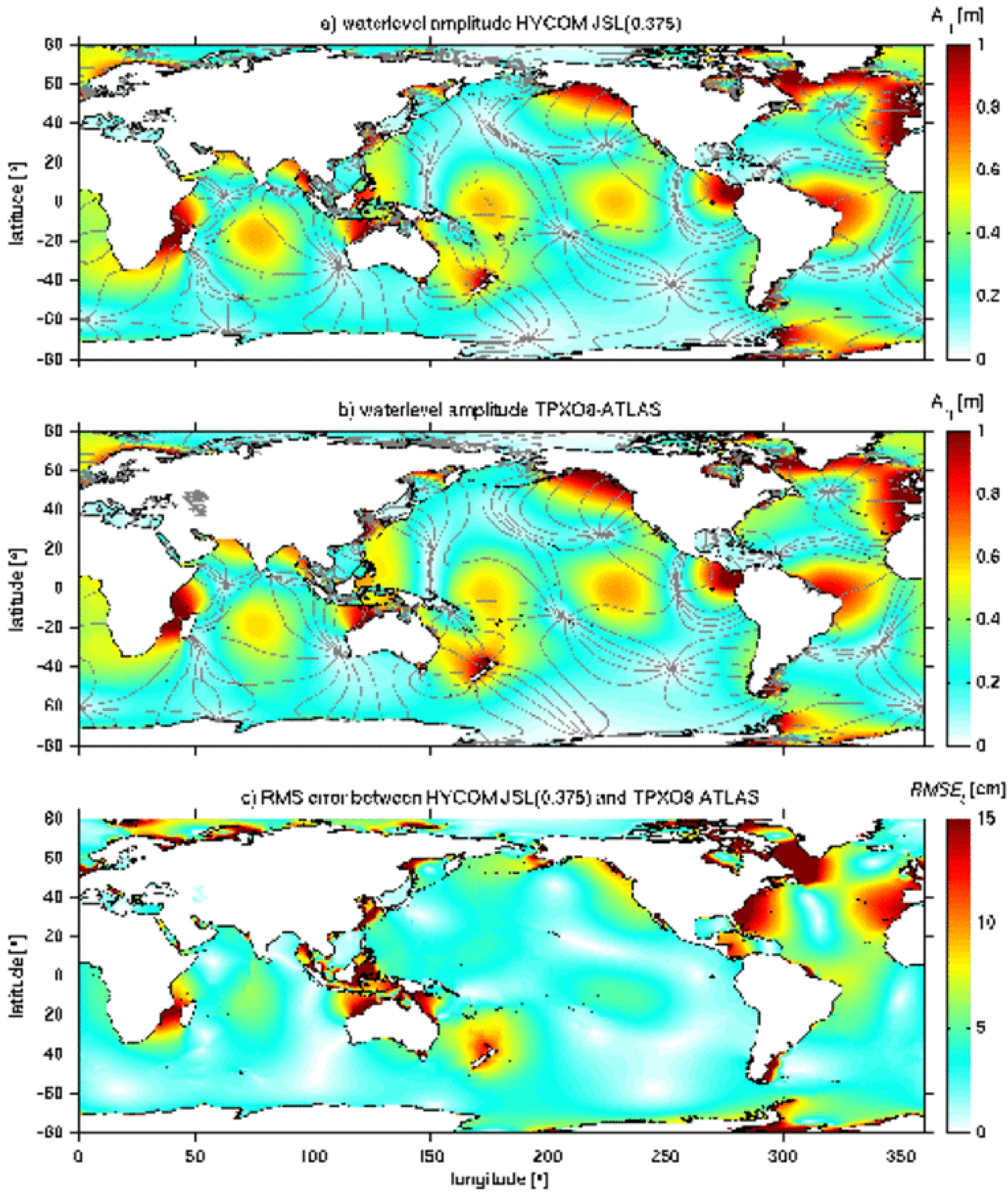

Figure 2. The M2 water level amplitude (m, colors) and phase (grey contours separated by 30°) for a) the HYCOM simulation with JSL and a scale factor of 0.375 and iterated SAL and b) the TPXO8-atlas. c) The water level RMS error (cm) between this HYCOM simulation and TPXO8-atlas.

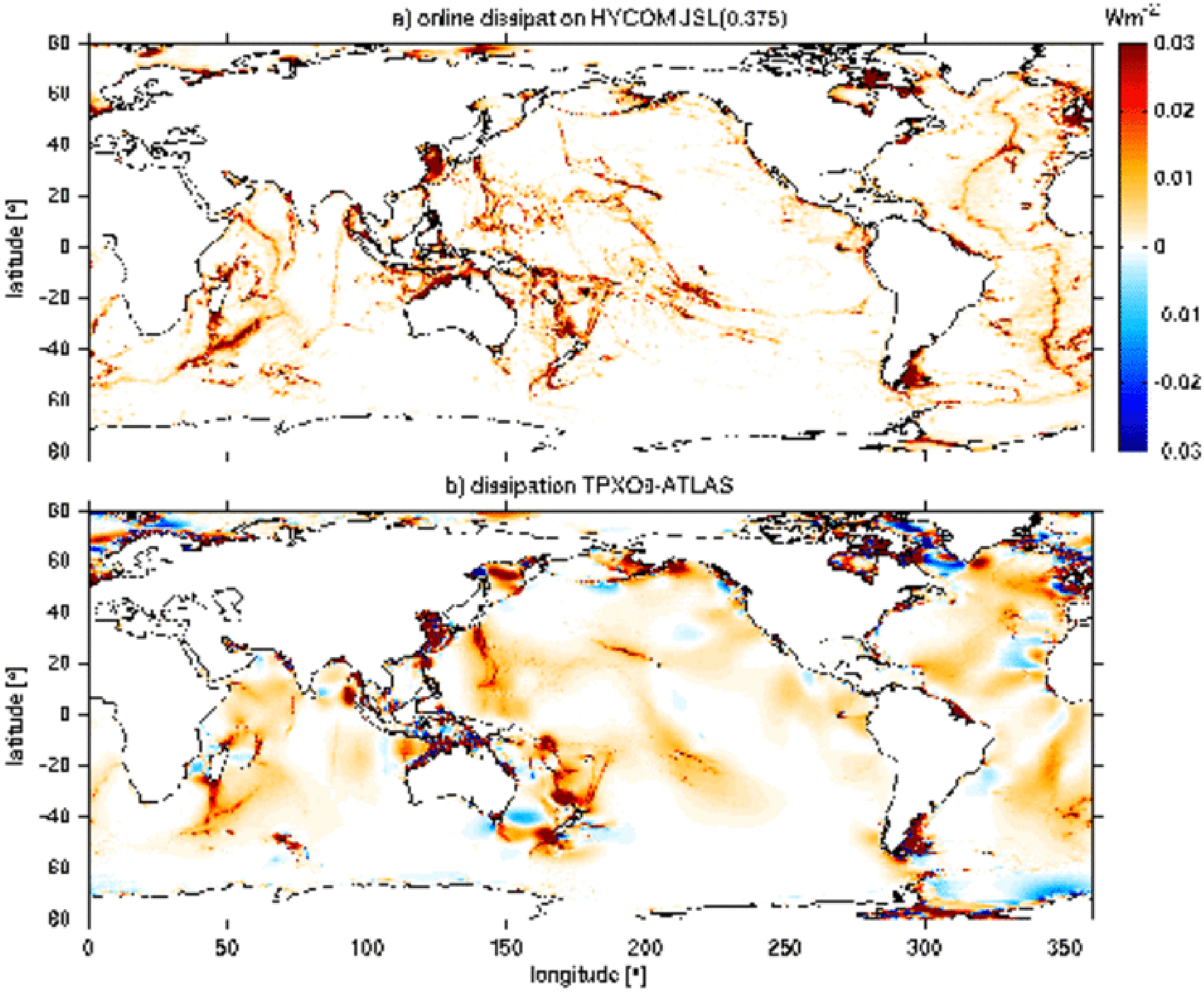

Figure 3. Global dissipation rates for (a) the HYCOM simulation with JSL and a scale factor of 0.375 and iterated SAL and (b) TPXO8-atlas.

A global tuning experiment for the semidiurnal tide was performed with a barotropic version of the HYbrid Coordinate Ocean Model (HYCOM). The model was forced with the M2 equilibrium tide and it accounted for the self-attraction and loading (SAL) term. In addition to a quadratic drag, various linear internal wave drag terms adjusted by a scale factor of O(1) are applied. The drag terms include the original Nycander [2005] tensor scheme, the Nycander tensor scheme reduced at supercritical slopes, and their scalar sisters, a Nycander scalar limited in shallow water, and the Jayne and St. Laurent [2001] (JSL) scalar scheme. The scalar Nycander schemes have slightly lower root-mean square (RMS) water level errors vs. the data-assimilative TPXO tide model than the tensor schemes. Although the simulation with the optimally tuned original Nycander scalar yields dissipation rates close to TPXO, its RMS is among the highest. The RMS error was lower for the reduced and depth-limited Nycander and JSL schemes, which place relatively more dissipation in deeper water. Figure 2 compares our best constant global scale factor case with TPXO8atlas. The RMS error is highest in the Atlantic, and the Atlantic needs a higher scale factor to be optimal than the Pacific and Indian Oceans. This makes it difficult to have each ocean basin optimally tuned with the application of a constant scale

factor. Our best global mean RMS error of 4.5 cm for areas deeper than 1000 m and equatorward of 66° is among the lowest obtained in a forward barotropic tide model. Figure 3a displays the sum of the linear and quadratic drag dissipation rates for the optimal JSL scheme with a scale factor of 0.375. The dissipation due to linear wave drag is largest at the mid-ocean ridges and island chains, such as Hawaii, whereas the dissipation due to quadratic drag is largest in the coastal shelf seas such as the European shelf. The dissipation maps for the other drag schemes have a similar appearance. TPXO does not assimilate tidal currents. Hence, its dissipation rates are not as reliable as its water levels. Nevertheless, we compare the simulated dissipation rates (Figure 3a) with the TPXO dissipation rates (Figure 3b). The latter rates are computed from the difference between the energy input and flux divergence as discussed in Egbert and Ray [2001]. The energy input and flux divergence terms are one order of magnitude larger than the "residual" dissipation rate. As a consequence of this noisy process, the global dissipation maps have areas with negative rates (Figure 3b, [Egbert and Ray, 2001]). Similar to the HYCOM dissipation rates in Figure 3a, the TPXO8-atlas dissipation rates are also large at rough topography and in coastal shelf seas. However, the deep-water dissipation rates are somewhat diffuse in Figure 3b.

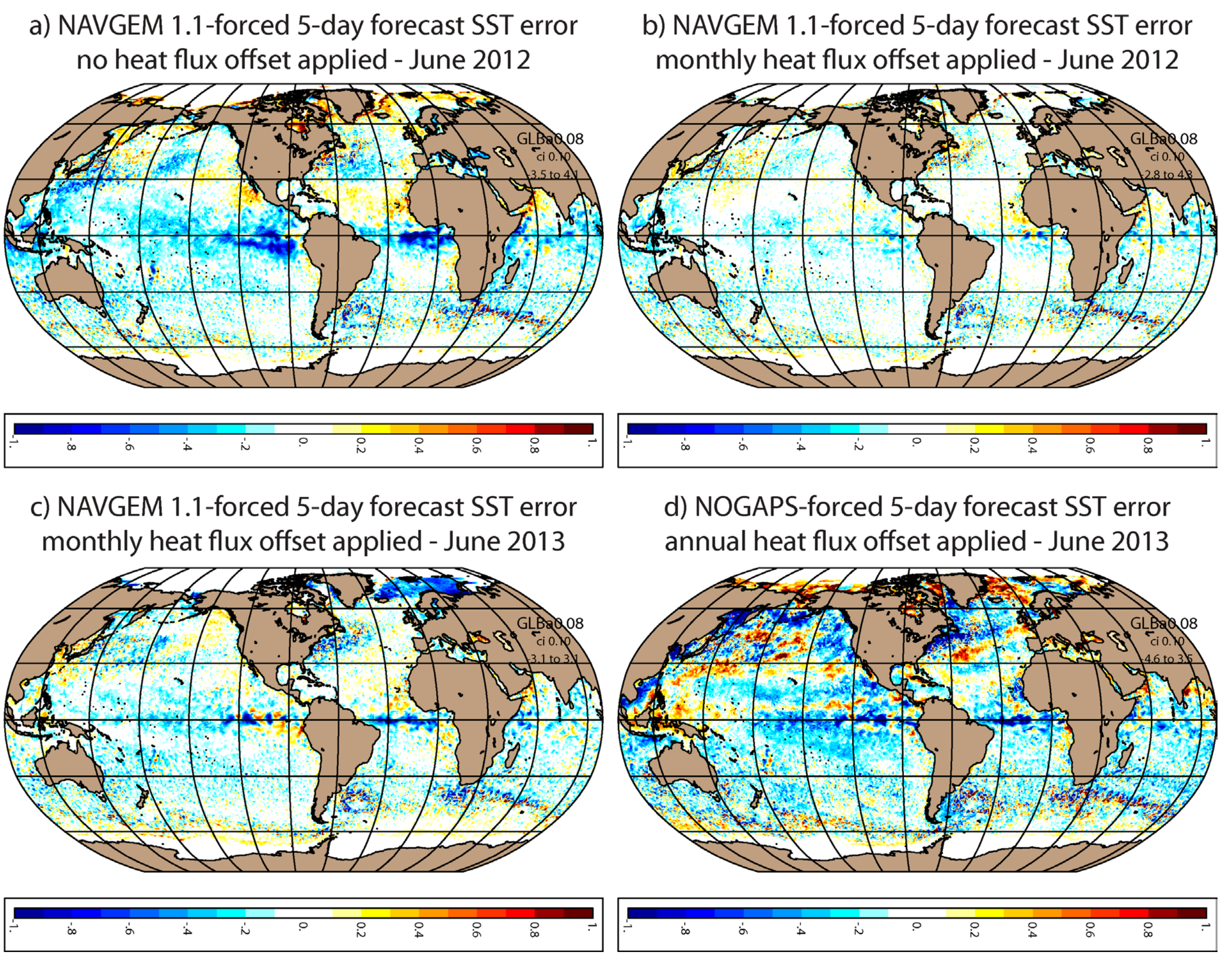

Figure 4. Five-day forecast SST error (°C) between the forecasts and the verifying analysis averaged over June 2012 (a,b) and June 2013 (c,d) with a) NAVGEM 1.1 forcing and no heat flux offset applied, b) NAVGEM 1.1 forcing and the monthly varying heat flux offset applied, c) NAVGEM 1.1 forcing and the monthly varying heat flux offset applied, and d) NOGAPS forcing and an annual mean heat flux offset applied.

The Navy Operational Global Atmospheric Prediction System (NOGAPS) was recently (13 March 2013) replaced by the NAVy Global Environmental Model (NAVGEM) as the U.S. Navy's operational atmospheric forecast system. NOGAPS was decommissioned on 31 August 2013 but before that date both the Global Ocean Forecast System (GOFS) and Arctic Cap Nowcast/Forecast System (ACNFS) had to switch from using NOGAPS to NAVGEM atmospheric forcing. Calibrations to the wind velocities and net heat flux were performed. Wind velocities were calibrated against contemporaneous satellite scatterometer data whereas heat flux was calibrated using 5-day forecast SST error. Figure 4 panels (a) and (b) show the 5-day forecast SST error for June 2012 with and without the heat flux calibration. Panel (c) shows the error in June 2013, a month not included in the training data set, and panel (d) shows the SST error from the equivalent NOGAPS forced case (which used an annual mean heat flux correction). The net impact is a reduction in 5-day forecast SST error and ice concentration error in the NAVGEM 1.1-forced system, compared to the NOGAPS-forced system. Overall, the methodology has been shown to be effective in minimizing upper ocean discontinuities when switching from one atmospheric product to another.

The GOFS 3.1 and GOFS 3.5 systems will also use NAVGEM 1.1 forcing. A candidate GOFS 3.1 system with NAVGEM is running as a hindcast and will be published on the hycom.org data server once it has reached the present day and is running in real time. The GOFS 3.5 system is completing its non-assimilative HYCOM+CICE spin-up with NAVGEM. We expect it to be running in real time with assimilation, but initially without tides, by the end of 2014.

IMPACT/APPLICATIONS

The 1/25° (3.5 km mid-latitude) resolution is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on 1/25° global HYCOM with tides, is planned to run in real-time starting in FY14 although initially without tides. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

TRANSITIONS

The Global Ocean Forecast System (GOFS) 3.01 with NOGAPS atmospheric forcing was declared operational at NAVOCEANO on 20 March 2013. It has since been upgraded to GOFS 3.02 with NAVGEM 1.1 atmospheric forcing. The Arctic Cap Nowcast/Forecast System (ACNFS) has passed its OPTEST at NAVOCEANO and will become an operational product in the near future.

RELATED PROJECTS

There are two related ONR funded projects, one at FSU COAPS under Eric Chassignet and the other at U. Michigan under Brian Arbic. Partnering projects at NRL include 6.1 Ageostrophic Vorticity Dynamics of the Ocean and its Impact on Frontogenesis, 6.1 Determining the Impact of Sea Ice

Thickness on the Arctic's Naturally Changing Environment (DISTANCE), 6.3 Ocean Reanalysis, 6.4 Earth System prediction Capability (ESPC), 6.4 Large Scale Ocean Modeling, 6.4 Ocean Data Assimilation, and 6.4 Ice Modeling Assimilation from Satellites. The computational effort is strongly supported by DoD HPC Challenge and NRL non-challenge grants of computer time. In FY13 all 1/25° global HYCOM+CICE cases ran under a FY13-15 DoD HPC Challenge grant.

REFERENCES

Arbic, B.K., A.J. Wallcraft and E.J. Metzger, 2010: Concurrent simulation of the eddying general circulation and tides in a global ocean model. Ocean Modelling, 32, 175-187.

Chin-Bing, S.A., A. Warn-Varnas, D.B. King, K.G. Lamb, M. Teixeira, and J.A. Hawkins, 2003: Analysis of coupled oceanographic and acoustic soliton simulations in the Yellow Sea: a search for soliton-induced resonances. Mathematics and Computers in Simulation, 62, 11-20.

Cummings, J.A., 2005. Operational multivariate ocean data assimilation. Quart. J. Royal Met. Soc., 131 (613), 3583-3604.

Egbert, G. D., and R. D. Ray (2001), Estimates of M2 tidal energy dissipation from TOPEX/Poseidon altimetry data, J. Geophys. Res., 106 (C10), 22,475–22,502.

Hill C., C. DeLuca, V. Balaji, M. Suarez, A. da Silva, 2004. The Architecture of the Earth System Modeling Framework. Computing in Science and Engineering, **6**, 18-28.

Hunke, E.C. and W.H. Lipscomb, 2004. CICE: the Los Alamos sea ice model documentation and software user's manual. http://climate.lanl.gov/Models/CICE

Jayne, S. R., and L. C. St. Laurent (2001), Parameterizing tidal dissipation over rough topography, Geophys. Res. Lett., 28, 811–814.

Nycander, J. (2005), Generation of internal waves in the deep ocean by tide, J. Geophys. Res., 110, C10028, doi:10.1029/2004JC002487.

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft and P.G. Timko, 2012: An Evaluation of the Barotropic and Internal Tides in a High Resolution Global Ocean Circulation Model. J. Geophys. Res. 117, C10024, doi:10.1029/2012JC008170.

Warn-Varnas, A.C., S.A. Chin-Bing, D.B. King, Z. Hallock, and J.A. Hawkins, 2003. Ocean-acoustic solitary wave studies and predictions. Surveys in Geophysics, 24, 39-79.

Warn-Varnas, A.C., S.A. Chin-Bing, D.B. King, J.A. Hawkins, K.G. Lamb, and J.F. Lynch, 2007. Winter PRIMER ocean-acoustic solitary wave modeling studies. IEEE J. Oceanic Engineering, 32(2), 436-452.

PUBLICATIONS

B. K. Arbic, K. L Polzin, R. B. Scott, J. G. Richman and J. F. Shriver, 2013: On Eddy Viscosity, Energy Cascades, and the Horizontal Resolution of Gridded Satellite Altimeter Products. Journal of Physical Oceanography vol 43, doi:10.1175/JPO-D-11-0240.1 [published, refereed]

Buijsman, M.C., A.J. Wallcraft, J.F. Shriver, R.W. Helber, J.A.M. Green, B.K. Arbic, and J.G. Richman, 2013: Optimizing Tides in a Forward Barotropic Model. J. Geophys. Res. [refereed]

J. A. Cummings and O. M. Smedstad, 2013: Variational Data Assimilation for the Global Ocean. Data Assimiltion for Atmospheric, Oceanic and Hydrologic Applications vol II, chapter 13. [published]

R. W. Helber, T. L. Townsend, C. N. Barron, J. M. Dastugue, and M. R. Carnes, 2013: Validation Test Report for the Improved Synthetic Ocean Profile (ISOP) System, Part 1: Synthetic Profile Methods and Algorithm. NRL Report NRL/MR/7320—13-9364. [published]

Metzger, E.J., O.M. Smedstad, P.G. Thoppil, J.A. Cummings, P.J. Hogan, H.E. Hurlburt, A.J. Wallcraft, and D.S. Franklin, 2012: A Global Ocean Nowcast/Forecast System Based on the 0.08° HYbrid Coordinate Ocean Model and the Navy Coupled Ocen Data Assimilation System. J. Marine Sci. [refereed]

Metzger, E.J., A.J. Wallcraft, P.G. Posey, O.M. Smedstad and D.S. Franklin, 2013: The Switchover from NOGAPS to NAVGEM 1.1 Atmospheric Forcing in GOFS and ACNFS, NRL Report NRL/MR/7320—13-9486. [published]

Posey, P.G., E.J. Metzger, R.A. Allard, R.H. Preller, D. Hebert, A.J. Wallcraft, M.W. Phelps, J. Hutchings, and O.M. Smedstad, 2013: Arctic Cap Nowcast/Forecast System (ACNFS) End of Summer 2013 Ice Extent Projection. Sea Ice Outlook Project website, June 2013. [published]

Posey, P.G., E.J. Metzger, R.A. Allard, R.H. Preller, D. Hebert, A.J. Wallcraft, M.W. Phelps, J. Hutchings, and O.M. Smedstad, 2013: Arctic Cap Nowcast/Forecast System (ACNFS) End of Summer 2013 Ice Extent Projection. Sea Ice Outlook Project website, July 2013. [published]

Posey, P.G., E.J. Metzger, R.A. Allard, R.H. Preller, D. Hebert, A.J. Wallcraft, M.W. Phelps, J. Hutchings, and O.M. Smedstad, 2013: Arctic Cap Nowcast/Forecast System (ACNFS) End of Summer 2013 Ice Extent Projection. Sea Ice Outlook Project website, August 2013. [published]

Posey, P.G., E.J. Metzger, R.A. Allard, R.H. Preller, D. Hebert, A.J. Wallcraft, M.W. Phelps, J. Hutchings, and O.M. Smedstad, 2013: Arctic Cap Nowcast/Forecast System (ACNFS) End of Summer 2013 Ice Extent Projection. Sea Ice Outlook Project website, September 2013. [published]

Richman, J.G., B.K. Arbic, J.F. Shriver, E.J. Metzger and A.J. Wallcraft, 2012: Inferring Dynamics from the Wavenumber Spectra of an Eddying Global Ocean Model with Embedded Tides. J. Geophys. Res., 117, C12012, doi:10.1029/2012JC008364. [published, refereed]

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft and P.G. Timko, 2012: An Evaluation of the Barotropic and Internal Tides in a High Resolution Global Ocean Circulation Model. J. Geophys. Res. 117, C10024, doi:10.1029/2012JC008170. [published, refereed]

Shriver, J.F., J.G. Richman, B.K. Arbic, R.D. Ray, E.J. Metzger and A.J. Wallcraft, 2012: How stationary are the internal tides in a high resolution global ocean circulation model? Proceedings of the "20 Years of Progress in Radar Altimetry" Symposium, 24-29 Sept 2012, Venice, Italy. [published]

Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E. J. Metzger, and A.J. Wallcraft, 2013: Skill testing a three-dimensional global tide model to historical current meter records. J. Geophys. Res. [refereed]

X. Xu, H. E. Hurlburt, W. J. Schmitz, R. Zantopp, J. Fischer, and P. J. Hogan, 2013: On the currents and transports connected with the atlantic meridional overturning circulation in the subpolar North Atlantic. Journal of Geophysical Research vol 118, doi:10.1002/jgrc,20065. [published, refereed]